

**EVALUATION OF THE POTENTIAL EFFECT OF CHLORIDE REDUCTION
ON TURBIDITY IN LAKE TEXOMA FOR THE RED RIVER CHLORIDE
CONTROL PROJECT, TULSA DISTRICT, OKLAHOMA**

by

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PREFACE

This study was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) in support to the U.S. Army Corps of Engineers, Tulsa District (TD), Red River Chloride Control Project above Lake Texoma on the Texas-Oklahoma border.

The study was conducted by Ms. Evelyn Toro and Ms. Elizabeth Fleming of the Environmental Restoration Branch (ERB), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES, and Dr. Paul R. Schroeder, Special Projects Group, EED. Mr. Steve Nolen of the Planning Division, TD, provided background materials, review of the study plan, and assistance in sample collection. The Environmental Chemistry Branch (ECB), EED, assisted with the chemical analysis of samples under the direction of Mr. Richard Karn.

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EVALUATION OF THE POTENTIAL EFFECT OF CHLORIDE REDUCTION ON TURBIDITY IN LAKE TEXOMA FOR THE RED RIVER CHLORIDE CONTROL PROJECT, TULSA DISTRICT, OKLAHOMA

1 INTRODUCTION

Background

The Red River and Lake Texoma are one of the few major rivers and large lakes in the United States that are saline or brackish in nature (1). The Red River runs through several states including Louisiana, Arkansas, Texas, and Oklahoma, and is one of the two most important water sources that feed Lake Texoma. Lake Texoma is a major source for recreational activities and potable water to residents in surrounding areas of Texas and Oklahoma. The high ionic content of its water, mainly chloride, sulfate, sodium and calcium, poses problems for domestic, agricultural and industrial use, requiring expensive and complex potable water treatment processes.

The U.S. Army Corps of Engineers, Tulsa District (TD), is initiating a chloride reduction project on the Red River above Lake Texoma, Oklahoma, to improve water supply. Total chloride and sodium concentrations are expected to be decreased by approximately 45%, while calcium and sulfate concentrations are expected to decrease slightly, about 5%.

Concerns for the environmental impacts that the Red River Chloride Control Project will present on the water quality at Lake Texoma have arisen. Lake Texoma's surface area presents approximately 89,000 acres of highly mineralized water committed mainly to recreation and fishing. The total dissolved solids concentration at Lake Texoma varies seasonally and spatially from about 700 to 1600 mg/l, with values greater than 1250 mg/l being common during normal and low flow periods. Chloride, sulfate, sodium, and calcium constitutes about 35, 25, 25, and 10 percent of the dissolved salts, respectively. Executing the chloride control project will decrease the total dissolved solids (TDS) during low to normal flow periods by approximately one-third of pre-project values. Concern has been raised that this decrease in TDS concentration will decrease the rate of sedimentation and yield more suspended solids and turbidity in Lake Texoma waters. The elevated turbidity could in turn reduce the productivity of the lake, reduce its recreational value, and otherwise impact its environmental quality.

The ionic strength of water impacts sedimentation by changing the stability of colloidal particles, in this case, clay and other natural detritus. Particles gain stability primarily by electrical forces due to charges on their surface or by hydration forces that provide a hydrophilic surface. TDS reduce the electrical forces by compressing the electrical double layer and the distance that electrical repulsion forces effectively act; this allows for more frequent collisions between particles that result in coagulation. Then, as coagulation proceeds, the size of the particle flocs grow until they are large enough to settle and overcome Brownian motion. In addition, TDS reduce the hydration forces by competing with the particles for the water. The thickness of the adsorbed water on the particles and the affinity of the particle for water are reduced, permitting easier aggregation of the particles. The change in TDS concentrations being proposed are rather small, and therefore it was impossible to determine the significance of the change without laboratory experimentation.

The U.S. Army Corps of Engineers, Waterways Experiment Station (WES), Vicksburg, Mississippi, in support to the Tulsa District, conducted a study on the impact that the Red River Chloride Control Project will have on turbidity in Lake Texoma. Several water quality parameters, including turbidity and total suspended solids, were measured through time to successfully accomplish the investigation.

Objectives

The objectives of the Lake Texoma study were:

- (1) to define the possible impact of a reduction in the TDS concentration in the Red River on the water clarity (turbidity) at Lake Texoma, Oklahoma and Texas;
- (2) to establish a relationship among TDS concentration, turbidity and sedimentation rate;
- (3) to determine if the variance in the decay rates can be attributed to the impacts of varying TDS concentrations or the initial turbidity using a two way analysis of variance (ANOVA) with replication; and
- (4) to determine if the differences in the final turbidity, percent removal of turbidity, and turbidity decay rate among the different test conditions (various levels of TDS and initial turbidity) are statistically different by comparing the means of the replicates with the Duncan's multiple range comparison test and the student's t-test.

2 DESCRIPTION OF WATER QUALITY PARAMETERS

The following chemical, physical and other common water quality parameters were used in the conduct of this study to rapidly and simply quantify and characterize the water quality and sedimentation processes.

Chemical Parameters

The chemical parameters measured in the study are related to the solvent capabilities and ionic composition of the water (2). Total dissolved solids, alkalinity and hardness are in this group of parameters, as well as individual ions including sodium, calcium, magnesium, potassium, chloride, and sulfate.

Total dissolved solids consist of organic and inorganic molecules and ions present in solution in water. Alkalinity is the capacity of the water to neutralize acids. The most common constituents of alkalinity are carbonate, bicarbonate, and hydroxide ions. High alkalinity imparts a bitter taste to water (2). Alkalinity plays an important role in the precipitation of many metal salts and in coagulation by ferric and aluminum salts. Hardness is defined as the concentration of multivalent metallic cations in solution (2). The reaction of these cations with the anions present in the water will form precipitates, which will contribute to the deposit of sludge or sediment. Multivalent cations also significantly promote coagulation, contributing to the ionic strength of the solution in quantities greater than the additive effect of its concentration.

Physical Parameters

The definition of physical water quality parameters has its fundamental basis on those characteristics that can be perceived by the human senses. Suspended solids, turbidity and temperature comprise the only physical water quality parameters measured in this study.

Suspended solids consist mainly of organic and inorganic matter common in surface waters, usually detritus of clay and biological solids such as algae. The presence of suspended material in natural water causes the absorbance, reflection or scattering of light. The measurement of the extent of this phenomena is referred as turbidity. Turbidity is commonly aesthetically displeasing, but it may also cause environmental impacts.

Interferences with the plants' photosynthesis may occur owed to reduced light penetration. Interference with aquatic life may also occur through feeding and/or respiratory problems. Increases in turbidity at Lake Texoma is expected to reduce the lake's productivity, thereby reducing fish population. Temperature affects the kinetic energy of the particles undergoing Brownian motion and, as such, impacts the turbidity decay rate as well as chemical reaction rates.

Other Parameters

Three other parameters were measured; they are pH, conductivity, and electrophoretic mobility. The pH is the concentration of the hydrogen ion and provides information related to the buffering capacity of water. Conductivity is the measurement of the movement of current through the water as a function of the ions in the water, providing information on ionic strength. The electrophoretic mobility (zeta potential) is related to the particle stability from electrical repulsion forces. Electrophoretic mobility is the velocity at which a particle moves in an imposed electric field (4). In natural waters the values are usually negative due to the negative charges on clay particle surfaces and ionization of acid groups on other particles. Colloidal particles stabilized by electrical repulsion tend to be unstable at mobilities less than $2 \mu\text{m}\cdot\text{cm}/\text{V}\cdot\text{sec}$, settling slowly at values between 0.5 and $2 \mu\text{m}\cdot\text{cm}/\text{V}\cdot\text{sec}$. Coagulation of electrically stabilized colloids can be achieved rapidly when its zeta potential approaches zero, usually between 5 to 10 mV or less (5). Particles with zeta potential between 10 and 40 mV are somewhat unstable and settle slowly.

3 TECHNICAL APPROACH

The development and accomplishment of the study were completed in phases:

Phase 1: Site water collection, water characterization, and suspension preparation.

Phase 2: Bench study of the impact of TDS concentration and initial turbidity on the turbidity as a function of time.

Phase 3: Data reduction and statistical analysis, including two way ANOVA with replication and comparison of means by Duncan's multiple range test and student's t-test.

Phase 1: Sample Preparation

Site Water Collection

WES, TD, and Texas Parks and Wildlife Department personnel collected approximately 125 gallons of water at Lake Texoma during morning hours of 8 May 1996. Water was collected from near the surface of the main pool northwest of Mill Creek Resort, approximately midway between the "islands" and the Willis bridge. The water was transported to WES by WES personnel and stored in a 4°C walk-in cooler until the start of the study.

Several water parameters were measured at the site; they are summarized in Table 1. In addition, the Secchi depth was measured to be 1.1 meters. Additional water samples were collected in 250-ml nalgene bottles at the site to be used for water chemistry analyses upon arrival at WES.

Water Characterization

Chemical analyses of the 250 ml samples were performed to characterize the ionic composition of the site water. The chemical analyses, which included chloride, sulfate, potassium, sodium, magnesium, calcium, total hardness and alkalinity, were performed by Environmental Chemistry Branch (ECB) personnel and will be described briefly in the Materials and Methods section. Physical water characteristics including turbidity and total

suspended solids, in addition to total dissolved solids, pH, and conductivity, were measured and recorded by Environmental Restoration Branch (ERB) personnel. Table 2 presents a summary of these analyses.

Table 1. Lake Texoma On-Site Water Parameters

Parameter	Depth (meters)	
	0.5	3.0
Temperature (°C)	20.08	16.66
Dissolved Oxygen (mg/L)	8.20	8.10
Conductivity (mS/cm)	2.67	2.69
pH	8.24	8.21

Table 2. Lake Texoma Water Characterization

Parameter	Sample ID		
	Texoma-001	Texoma-002	Mean
Chloride (mg/l)	453	460	456.5
Sulfate (mg/l)	358	362	360.0
Potassium (mg/l)	5.99	5.64	5.82
Sodium (mg/l)	331	329	330.0
Magnesium (mg/l)	58.4	49.7	54.1
Calcium (mg/l)	165	148	156.5
Total Hardness (mg/l of CaCO ₃)	653	574	613.5
Alkalinity (mg/l of CaCO ₃)	117	120	118.5
Total Dissolved Solids (mg/l)	1545	1590	1567.5
Total Suspended Solids (mg/l)	7.5	7.5	7.5
Conductivity (mS/cm)	2.55	2.52	2.54
Turbidity (NTU)	6.0	6.0	6.0
pH	7.88	7.93	7.91

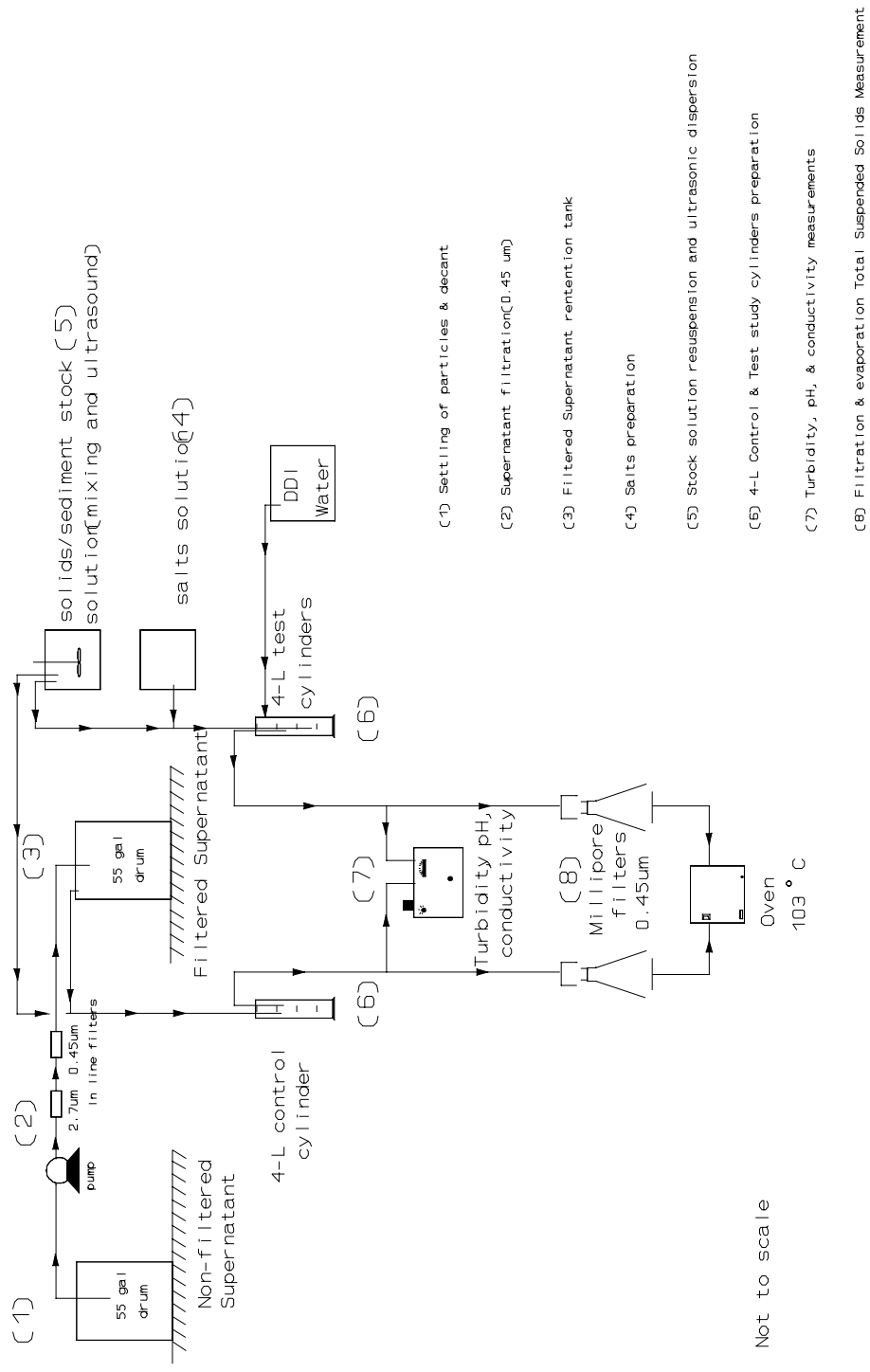
Suspension Preparation

Upon arrival at WES, the water was transferred and stored in two 55-gallon open top polyethylene barrels. After about 5 days of settling, the supernatant was decanted and filtered. Ninety percent of the total water was removed by decanting and then filtered through an in-line 2.7 μm *Whatman GF/D* and a 0.45 μm *Quick Filter* using *Masterflex* peristaltic pumps. The water characteristics of the filtered supernatant were measured by chemical analyses to verify that the preparation process did not change the water composition significantly. The results are reported in Table 3. The ECB laboratory raw data sheets for these analyses and for other chemical analyses presented in this report are included in Appendix F. The remaining ten percent of the solution (sediment) from the two 55-gallon barrels was stored in a 32-gallon plastic container for preparation of the stock turbidity suspension. Figure 1 shows a summary of the study system set-up. A brief description for each process is included.

Table 3. Lake Texoma Filtered Supernatant Water Characterization

Parameter	Sample ID		
	Texoma-003	Texoma-004	Mean
Chloride (mg/l)	486	487	486.5
Sulfate (mg/l)	386	384	385
Potassium (mg/l)	6.47	6.51	6.49
Sodium (mg/l)	336	345	340.5
Magnesium (mg/l)	53.2	54.8	54.0
Calcium (mg/l)	160	163	161.5
Total Hardness (mg/l of CaCO_3)	619	633	626
Alkalinity (mg/l of CaCO_3)	119	118	118.5
Total Dissolved Solids (mg/l)	1667	1607	1637
Total Suspended Solids (mg/l)	0	0	0
Conductivity (mS/cm)	2.64	2.60	2.62
Turbidity (NTU)	0.7	1.0	0.9
pH	7.15	7.02	7.09

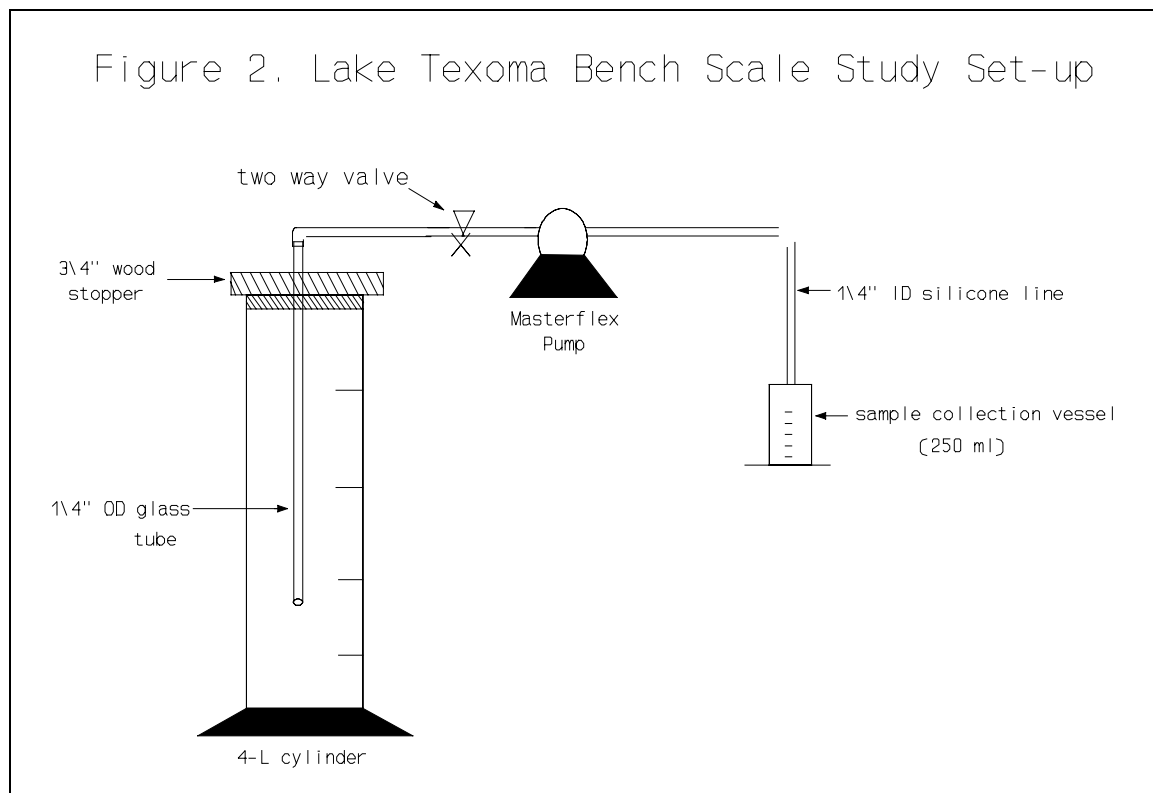
Figure 1. Lake Texoma Water Clarity Study System Set-up



Phase 2: Bench Study

Ten sets of sedimentation tests were conducted in 4-litre cylinders, five in triplicate using an initial turbidity of 8 NTU and five in duplicate using an initial turbidity of 16 NTU. Each group of five sedimentation tests contained one set of tests at each the following five TDS concentrations: 1600, 1120, 838, 670, and 519 mg/l. These TDS concentrations correspond respectively to the initial TDS concentrations (control), a transition concentration, and the TDS concentrations that are expected to be exceeded 5%, 50% and 95% of the time following implementation of the chloride reduction project. The corresponding chloride and sulfate concentrations for these five TDS concentrations are 486, 292, 248, 198 and 148 mg Cl⁻/l, and 385, 300, 282, 226 and 150 mg SO₄⁻²/l, respectively. Figure 2 shows the bench scale setup.

The five different TDS conditions were prepared mixing one part of stock suspension with its original TDS concentration with three parts of a prepared solution of dissolved salts. Two common salts, calcium chloride (CaCl₂) and magnesium sulfate (MgSO₄), were dissolved in deionized distilled water (DDI) to create the three parts of salt solution required to reach the targeted TDS concentrations. Calculation of the quantity of each salt to be added for each different TDS level was based on the previous chemical analysis of the natural water and filtrate and the target TDS, chloride, and sulfate concentrations. The control cylinder was diluted with three parts of filtered supernatant, reproducing the natural water condition.



Resuspension and dispersion of the stock solution was accomplished by constant mixing, followed by ultrasonic treatment, which increased turbidity of the stock suspension by approximately ten units (about 30%). The start of the sedimentation was marked by the mixing of the filtrate and stock solution for the control and by the mixing of the salt and stock solutions for the target conditions. The total duration of the test was seven days. Throughout the test period, turbidity, conductivity, pH, and TSS were measured and recorded at intervals sufficient to capture the changes in turbidity. Detail discussion follows in the Results section.

Samples were collected intermittently throughout the seven days of sedimentation by pumping about 200 ml from mid-depth of the cylinder through a glass tube and Tygon tubing. The sample was then analyzed for pH, conductivity, turbidity and suspended solids, as appropriate.

Phase 3: Data Reduction and Analyses

The turbidity data for each treatment and replicate was reduced in several manners for later statistical analyses. First, linear regression was performed on a log transform of the ratio of turbidity to initial turbidity versus time to determine the turbidity decay rate of each replicate for all treatments. The mean turbidity and standard deviation of the replicates were computed for each treatment and time period. The percent removal was calculated for each replicate, treatment and time period, as well as the mean percent removal and standard deviation for each treatment and time period.

Using the reduced data, two-way ANOVA with replication was performed on the computed turbidity decay (sedimentation) rates to determine whether the variances in the data were attributable to the treatments and whether the differences between treatments were statistically significant. In this test TDS concentration and initial turbidity were the two treatments, and the replicates provided a measure of errors. Upon demonstrating that the effects of initial turbidity were statistically significant, one-way ANOVA and Duncan's multiple range test were run twice, once on the computed turbidity decay rates for test conditions having an initial turbidity of 8 NTU and the other on the computed turbidity decay rates for test conditions having an initial turbidity of 16 NTU. These analyses were run to determine whether the mean values of the replicate turbidity decay rates at the various treatment levels were statistically different. The decay rates between the two different initial turbidity conditions at the same TDS concentration were compared using a student's t-test. These same procedures were used on the final turbidity values (after 7 days of settling) and on the final percent removal of turbidity as well as the removals after two days of settling.

4 MATERIALS AND METHODS

Materials

This section contains a brief description of the equipment and chemicals used during the study.

Equipment

Cole-Palmer Masterflex peristaltic pump Model 75553-70 was used to pump out the filtrate from the drums. Two in-line filters, a 2.7 μm *Whatman GF/D* and a 0.45 μm *Quick Filter*, were used to filter the supernatant.

Four-litre transparent polymethylpentene cylinders were used as the bench scale settling columns. A wood stopper was cut, laminated, and placed in the opening at the top of the cylinders to close the system and prevent contamination. An orifice in the center of the wood stopper allowed for the insertion of a 1/4-inch outside diameter (OD) glass tube into the cylinder for sampling. Attached to the tube outside the cylinder was 1/4-inch ID silicon tubing connected to a *Nalgene* two-way stopcock and a *Cole-Palmer Masterflex* peristaltic pump Model 75553-70 for sample collection.

For the stock resuspension, a *Lightnin Labmaster* variable speed mixer was used. Ultrasonic dispersion was achieved using a *Cole-Palmer* ultrasonic processor Model GB 600 at 40% of the total power (600 Watts) for a period of ten minutes.

The turbidity was measured using a *HF Scientific* turbidimeter Model DRT-100 calibrated with a 0.02 NTU reference standard. The pH was read using a *Beckman* pH meter Model 45 with two-point calibration standards, pH 4 and pH 10. The conductivity measurements were obtained using a *TraceableTM* digital conductivity meter.

The total dissolved solids and suspended solids were dried respectively at 180°C and 103 \pm 2°C in a *Precision Scientific Group* mechanical conventional oven Model 28. A *Millipore* filtration apparatus with 0.45- μm *Millipore* HAPW filters was used for filtering during the solids measurements. A *Mettler* balance Model AE240 was used to weigh the solids samples.

Electrophoretic mobility was measured using a *Coulter* laser doppler velocimeter and electrophoretic light scattering apparatus (DELSA Model 440). Electrophoretic mobilities

were measured at both the upper and lower stationary locations in the cell using four angles of light scattering, 8.6°, 17.1°, 25.6° and 34.2°. The frequency range was set at 500 Hz using a frequency shift of 250 Hz. Measurements were taken using a current of 0.5 mA at 25 °C. Zeta potential was calculated from the electrophoretic mobility measurement using information on ionic strength from analysis of ionic composition and total dissolved solids and microscopic observation of particle size, as well as tabulated values of viscosity and other physical parameters for water.

Chemicals

Calcium chloride-dihydrated ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$), magnesium sulfate (MgSO_4), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4) salts, obtained from Mallinckrodt, J. T. Baker, GFS Chemicals, and Aldrich Companies respectively, were used in the study. The salts were dissolved in DDI water.

Methods

Table 4 contains brief descriptions of the methods used in the analysis of many of the parameters measured in this study, including the detection limits, the analysis methods, and the instrumentation. The majority of the water-quality chemical analyses were performed by the ECB. These included ionic composition, hardness, and alkalinity.

Table 4. Analysis Methods and Instrumentation Descriptions

Parameter	Method	Instrumentation	Detection Limit (mg/l)
Ca ⁺²	EPA SW-846-Method 6010A	Inductively Coupled Plasma (ICP) Emission Spectroscopy	0.1
Mg ⁺²	EPA SW-846-Method 6010A	Inductively Coupled Plasma (ICP) Emission Spectroscopy	0.2
K ⁺	EPA SW-846-Method 6010A	Inductively Coupled Plasma (ICP) Emission Spectroscopy	1.0
Na ⁺	EPA SW-846-Method 6010A	Inductively Coupled Plasma (ICP) Emission Spectroscopy	0.1
Alkalinity*	Lachat Method No. 10-303-31-1-A	Lachat 8000 Flow Injection Analyzer	0.010-0.500
SO ₄ ⁻²	EPA SW-846-Method 9056	Dionex Ion Chromatograph DX100	0.375
Cl ⁻	EPA SW-846-Method 9056	Dionex Ion Chromatograph DX100	0.375
Hardness	Standard Methods Handbook 2340B	Calculation through Ca ⁺² and Mg ⁺² Ions (obtained by ICP)	N/A**
TSS	Standard Methods Handbook 2540D	Filtration and Conventional Oven Dried at 103-105°C	N/A**
TDS	Standard Methods Handbook 2540C	Filtration and Conventional Oven Dried at 180°C	N/A**

* Reported as mg/l of CaCO₃

** N/A: Not applicable

5 RESULTS AND DISCUSSION

Sedimentation Rates

The turbidity data generated during the study are summarized in Tables A1 through A12 (Appendix A). A linear regression analysis was performed with this data, as shown in Appendix B and Figures 3 through 31 (Appendix B). The regression plots exhibited a first order decay or sedimentation rate which follows the equation:

$$N = N_0 e^{-k t}$$

where N is the turbidity at a certain time, N_0 is the initial turbidity ($t = 0$), and k is the sedimentation rate constant (1/hour).

The linear regression for each condition replicate allowed for the determination of a mean sedimentation rate constant for each specific target TDS concentration and initial turbidity level studied. Table 5 summarizes the mean sedimentation constants for each condition studied. The variance (σ^2) and standard deviation (σ) are also included in this table. The mean sedimentation rates for the test conditions employing dilution with DDI water are plotted in Figure 3 as a function of the TDS concentration.

Table 5 shows that slightly lower rates of sedimentation were obtained with an increase in the initial turbidity level in the majority of the cases. However, it should be noted that the pH of the stock suspension was decreasing with time throughout the study and may be contributing to this effect. The pH dropped from about 8.3 to 7.3 during the month of sample preparation and testing; differences in the pH between the first and last tests were about 0.7 pH units. Conductivity and pH data are given in Appendix D. Increases in the total dissolved solids concentration exhibited small increases in the sedimentation rate. A comparison of these variables are obtained through statistical analysis of variances and means testing. Table 5 also shows the control and the laboratory created test conditions behaved differently. The sedimentation rate for the controls were lower than the tests with lower TDS concentrations prepared with salts and DDI water or just DDI water (Test Condition 11 in Table 5). An additional test, Test Condition 12 in Table 5, was conducted in which the TDS concentration of the control was reproduced using DDI water and four different salts: NaCl, Na₂SO₄, CaCl₂, and MgSO₄. However, for all of the test conditions prepared with DDI water, there is a smooth trend in the results; the sedimentation rate decreases with decreases in the TDS

concentration. The differences in the controls can only be attributed to differences between the filtrate and the DDI water.

Table 5. Sedimentation Rate Constants

Test Condition		Mean k (1/hours)	Variance σ^2	Standard Deviation σ
#	Description			
1*	1600 mg/l TDS; 486 mg/l Cl ⁻ ; 385 mg/l SO ₄ ⁻² ; 8 NTU	0.00562	4.55E-07	0.0006749
2	1120 mg/l TDS; 292 mg/l Cl ⁻ ; 300 mg/l SO ₄ ⁻² ; 8 NTU	0.01690	1.77E-06	0.0013319
3	838 mg/l TDS; 248 mg/l Cl ⁻ ; 282 mg/l SO ₄ ⁻² ; 8 NTU	0.01437	4.70E-07	0.0006856
4	670 mg/l TDS; 198 mg/l Cl ⁻ ; 226 mg/l SO ₄ ⁻² ; 8 NTU	0.01316	1.43E-06	0.0011964
5	519 mg/l TDS; 148 mg/l Cl ⁻ ; 150 mg/l SO ₄ ⁻² ; 8 NTU	0.01135	1.17E-07	0.0003424
6*	1600 mg/l TDS; 486 mg/l Cl ⁻ ; 385 mg/l SO ₄ ⁻² ; 16 NTU	0.00522	1.92E-07	0.0004384
7	1120 mg/l TDS; 292 mg/l Cl ⁻ ; 300 mg/l SO ₄ ⁻² ; 16 NTU	0.01528	1.46E-07	0.0003818
8	838 mg/l TDS; 248 mg/l Cl ⁻ ; 282 mg/l SO ₄ ⁻² ; 16 NTU	0.01457	4.21E-08	0.0002051
9	670 mg/l TDS; 198 mg/l Cl ⁻ ; 226 mg/l SO ₄ ⁻² ; 16 NTU	0.01176	1.25E-09	0.0000354
10	519 mg/l TDS; 148 mg/l Cl ⁻ ; 150 mg/l SO ₄ ⁻² ; 16 NTU	0.00916	2.11E-07	0.0004596
11**	400 mg/l TDS; 122 mg/l Cl ⁻ ; 96 mg/l SO ₄ ⁻² ; 16 NTU	0.00696	8.00E-10	0.0000283
12***	1600 mg/l TDS; 486 mg/l Cl ⁻ ; 385 mg/l SO ₄ ⁻² ; 16 NTU	0.01358	2.38E-07	0.0004879

* Control, no salts added, composed of stock suspension and filtrated supernatant.

** No salts added, composed of deionized, distilled water and stock suspension.

*** Salts and DDI water added to stock suspension at concentrations equal to the control.

Attempts were made to measure suspended solids concentrations in Test Conditions 1 through 5, but the amount of suspended solids in the Lake Texoma water was too low to obtain reliable data with a sample size of 200 ml. The results are given in Tables E1 through E12 in Appendix E.

The electrophoretic mobility of one replicate from each of Test Conditions 1 through 11 was measured to verify that the particles were stabilized primarily by electrical repulsion forces and that the trends in the sedimentation rates followed the trends in the electrophoretic mobility measurements and computed zeta potentials. The mean of the mean and modal values from the two locations at the four angles for light scattering are given in Table 6. The laboratory data are presented in Appendix G.

Table 6. Electrophoretic Mobility and Zeta Potential Values

Test Condition	Electrophoretic Mobility ($\mu\text{m} \cdot \text{cm}/\text{V} \cdot \text{sec}$)		Computed Zeta Potential (mv)
	Mode	Mean	Mean
1	-1.77	-1.64	-21.0
2	-0.18	-0.43	-5.5
3	-1.20	-1.06	-13.7
4	-0.77	-0.89	-11.5
5	-1.26	-1.32	-16.9
6	-1.38	-1.29	-16.6
7	-0.51	-0.67	-8.6
8	-0.98	-1.03	-13.2
9	-0.80	-0.79	-10.1
10	-1.31	-1.34	-17.1
11	-1.64	-1.52	-19.5

Percent Removal of Turbidity

The mean of the turbidity of the replicates following 2 and 7 days of settling are given in Table 7 along with the percent removals. These means are compared statistically to determine whether the differences are significant. The differences are time dependent

because given enough time the means and their differences for all test conditions will approach zero.

Table 7. Select Turbidity and Removal Results

Test Condition	Turbidity (NTU)			% Removal	
	Initial	2 days	7 days	2 days	7 days
1	8.10	6.43	2.97	20.89	63.56
2	8.40	4.13	0.45	50.63	94.56
3	8.17	4.47	0.75	45.28	90.84
4	8.37	4.87	0.85	41.81	89.83
5	8.80	5.37	1.33	39.15	84.91
6	16.50	11.00	6.95	33.27	57.80
7	15.00	4.75	1.35	68.31	90.94
8	16.00	5.80	1.65	63.76	89.69
9	16.00	6.95	2.55	56.57	84.07
10	16.50	8.40	3.65	49.08	77.83
11	15.00	11.00	4.70	26.67	68.67
12	15.50	7.40	1.80	52.09	88.38

Statistical Analyses

The sedimentation rates, turbidity, and percent removal for the different test conditions were compared using a commercial software program called NWA STATPAK from Northwest Analytical, Inc., Portland, Oregon. Appendix C contains the detailed results for the two-way ANOVA, one-way ANOVA, Duncan's multiple range test and student's t-test performed on the study data.

Sedimentation Rate (k)

A two-way ANOVA was performed to determine how much of the variance in the sedimentation rate population was attributable to differences in the TDS concentration, initial turbidity, and replicates (error). The results show that the differences in the TDS concentration accounted for more than 90 percent of variance, while initial turbidity

accounted for about 7 percent of the variance. Covariance contributed about 1.2 percent and errors about 0.7 percent of the variance. Therefore, differences in the TDS concentration cause differences in sedimentation rate with greater than a 99.99 percent probability. Similarly, differences in the initial turbidity cause differences in the sedimentation rate with greater than a 99 percent probability.

Comparisons of the sedimentation rates among the tests conducted with an initial turbidity of 8 NTU using the Duncan's multiple range test show that the mean sedimentation rates for each test condition (1 through 5) are different from each other with greater than a 99 percent probability except conditions 4 and 5 and conditions 3 and 4. Conditions 4 and 5 were different at a 95 percent probability. Conditions 3 and 4 were not significantly different.

Comparisons of the sedimentation rates among the tests conducted with an initial turbidity of 16 NTU using the Duncan's multiple range test show that the mean sedimentation rates for each test condition (6 through 10) are different from each other with greater than a 99 percent probability except conditions 7 and 8. Conditions 7 and 8 were not significantly different.

Comparisons of the sedimentation rates between the two tests conducted with the same TDS concentration (different initial turbidity) using the student's t-test show that the mean sedimentation rates at different initial turbidity are not significantly different except at the lowest TDS level (519 mg/l). The probability that the sedimentation rate is different at 519 mg/l TDS is 95 percent.

Comparisons were also made between the additional test conditions (11 and 12) and the control (Test Condition 6). The results show that the sedimentation rates for these conditions are different with greater than a 99 percent probability. This indicates that the use of DDI water and filtrate produced statistically different results.

Final Turbidity

A two-way ANOVA was performed to determine how much of the variance in the final (7-day) turbidity population was attributable to differences in the TDS concentration, initial turbidity, and replicates (error). The results show that the differences in the TDS concentration accounted for 85 percent of variance, while initial turbidity accounted for about 13 percent of the variance. Covariance contributed about 0.7 percent and errors about 0.7 percent of the variance. Therefore, differences in the TDS concentration cause differences in the final turbidity with greater than a 99.99 percent probability. The probability that differences in the initial turbidity cause differences in the final turbidity was greater than 99.8 percent.

Comparisons of the final turbidity for the various test conditions using the Duncan's multiple range test show that some of the final turbidities were significantly different with a 99% level of confidence, while others were not significantly different even at a 95%

level of confidence. Only the final turbidity for the control and the lowest TDS concentration (Test Conditions 1 and 5) were significantly different from all five conditions with the low initial turbidity (Test Conditions 1 through 5). For the test conditions with the higher initial turbidity, the final turbidity of all five TDS concentrations were significantly different at a 99 percent level of confidence except that the differences between the final turbidities for Test Conditions 7 and 8 were not significantly different even at a 95% level of confidence. Comparisons of the final turbidities between the two tests conducted with the same TDS concentration (different initial turbidity) using the student's t-test show that the mean final turbidities at all TDS concentrations were significantly different at a 95% level of confidence.

Percent Removal of 7-Day and 2-Day Turbidity

A two-way ANOVA was performed to determine how much of the variance in the final (7-day) percent removal of turbidity population was attributable to differences in the TDS concentration, initial turbidity, and replicates (error). The results show that the differences in the TDS concentration accounted for over 85 percent of variance, while initial turbidity accounted for about 13 percent of the variance. Covariance contributed about 0.7 percent of the variance and errors about 0.7 percent. Therefore, differences in the TDS concentration cause differences in the final percent removal of turbidity with greater than a 99.99 percent probability. The probability that differences in the initial turbidity cause differences in the final removal percentage was greater than 99.8 percent.

Comparisons of the final turbidity removal percentage for the various test conditions using the Duncan's multiple range test show that some of the final removals were significantly different with a 99% level of confidence, while others were not significantly different even at a 95% level of confidence. As with the final turbidity, the final removal percentages for the control and the lowest TDS concentration (Test Conditions 1 and 5) were significantly different from all five conditions with the low initial turbidity (Test Conditions 1 through 5). For the test conditions with the higher initial turbidity, the final turbidity removal percentages of all five TDS concentrations were significantly different at a 95 percent level of confidence, and for all but one at a 99 percent level of confidence, except that the differences between the final removal percentages for Test Conditions 7 and 8 and for Test Conditions 8 and 9 were not significantly different even at a 95% level of confidence. Comparisons of the final removal percentages between the two tests conducted with the same TDS concentration (different initial turbidity) using the student's t-test show that the mean final removal percentages at all TDS concentrations were not significantly different at a 95% level of confidence, though the values for the two lowest TDS concentration were different at a 90% level of confidence.

A two-way ANOVA was performed to determine how much of the variance in the 2-day turbidity removal percentage population was attributable to differences in the TDS concentration, initial turbidity, and replicates (error). The results show that the differences in the TDS concentration accounted for about 36 percent of variance, while initial turbidity accounted for over 62 percent of the variance. Covariance contributed about 0.7 percent and errors about 0.6 percent of the variance. Therefore, differences in the TDS

concentration cause differences in the 2-day turbidity removal percentage with greater than a 99.99 percent probability. The probability that differences in the initial turbidity cause differences in the 2-day turbidity removal percentage was also greater than 99.99 percent.

Comparisons of the 2-day turbidity removal percentage for the various test conditions using the Duncan's multiple range test show that the removals were not significantly different with a 95% level of confidence except for a few cases. The controls were significantly different from the other TDS levels at a 99% level of confidence. For the lower initial turbidity conditions only Test Condition 2 differed from Test Conditions 4 and 5 with a 95% level of confidence. For the higher initial turbidity conditions only Test Conditions 7 and 8 did not differ with a 95% level of confidence.

Comparison of Pre- and Post-Project Conditions

The change in turbidity due to the project following a disturbance in Lake Texoma is a function of the TDS concentration present, the size of the disturbance (initial turbidity), and the time since the disturbance. To compare pre- and post-project conditions, it is necessary to compare the effects of changes in sedimentation rates at various frequencies of occurrences. The pre- and post-project concentration-duration levels are given in Table 8. The lab conditions were set at projected levels which would be exceeded 5, 50 and 95% of the time following construction of the project and sedimentation rates were computed from the lab data at these levels as well as a couple other levels. To estimate the comparable pre-project and post-project sedimentation rates for TDS concentrations that are presently exceeded 5, 50, 95 and 99% of the time based on the laboratory conditions, the rates are obtained from Figure 3. The computed sedimentation rates from the regression curves in Figure 3 are given below in Table 9. Figure 3 contains a plot of the sedimentation rates for dilutions with DDI water at initial turbidities of 8 and 16 NTU.

To examine the relative response of pre- and post-project conditions, comparisons of turbidity versus time are given in Figures 4 through 11 for four frequencies of occurrence at two locations and two initial turbidity levels. The average condition in Lake Texoma is between the conditions at Reach 5 and Reach 6 but the two locations should provide a representative range of results. Comparison of the curves in these figures yield the maximum differences in turbidity between pre- and post-project conditions following an introduction of turbidity and when the maximum difference occurs after the introduction of turbidity. These results are presented in Table 10.

The results in Table 10 show that a disturbance during 50 percent of the time following implementation of the project yields a maximum increase in turbidity of less than 1 NTU above that which would occur prior to implementation of the project. This increase occurs 2 to 3 days after the disturbance. Differences greater than half of the

Table 8. Pre- and Post-Project Concentration-Duration Data*

Location	Frequency Concentration Exceeded (percent)	TDS Concentration (mg/L)		Chloride Concentration (mg/L)		Sulfate Concentration (mg/L)	
		Pre-	Post-	Pre-	Post-	Pre-	Post-
Reach 5 Lake Texoma Dam	1	1350	904	480	264	320	301
	5	1250	838	450	248	300	282
	20	1200	804	410	226	275	258
	50	1000	670	360	198	240	226
	80	880	590	300	165	190	179
	95	775	519	270	148	160	150
	99	700	469	220	121	140	132
Reach 6 Red River at Entrance to Lake Texoma	1	4500	4100	2000	1750	1000	860
	5	3800	3000	1700	1200	800	695
	20	3400	1800	1350	610	660	610
	50	2800	1200	1100	315	560	485
	80	1700	780	660	108	340	318
	95	900	475	350	39	180	175
	99	500	150	150	14	100	100

* from Appendix D, Concentration-Duration Curves, Limited Reevaluation Report, Red River Chloride Control Project, June 1993.

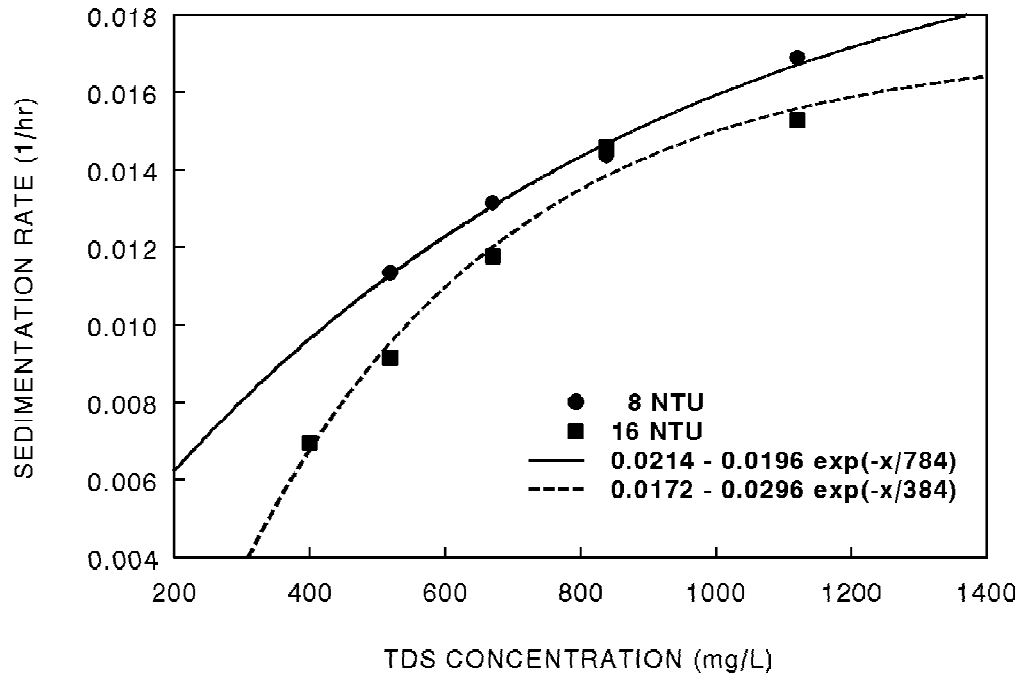


Figure 3. Sedimentation rate as a function of TDS concentration and initial turbidity.

Table 9. Pre- and Post-Project Sedimentation Rates

Location	Frequency Concentration Exceeded (percent)	Sedimentation Rate (hr ⁻¹)			
		8 NTU		16 NTU	
		Pre-	Post-	Pre-	Post-
Reach 5 Lake Texoma Dam	5	0.01743	0.01468	0.01605	0.01385
	50	0.01594	0.01307	0.01500	0.01218
	95	0.01412	0.01130	0.01326	0.00995
	99	0.01339	0.01064	0.01241	0.00846
Reach 6 Red River at Entrance to Lake Texoma	5	0.02126	0.02098	0.01719	0.01718
	50	0.02086	0.01717	0.01717	0.01589
	95	0.01519	0.01072	0.01435	0.00860
	99	0.01105	0.00526	0.00914	0.00432

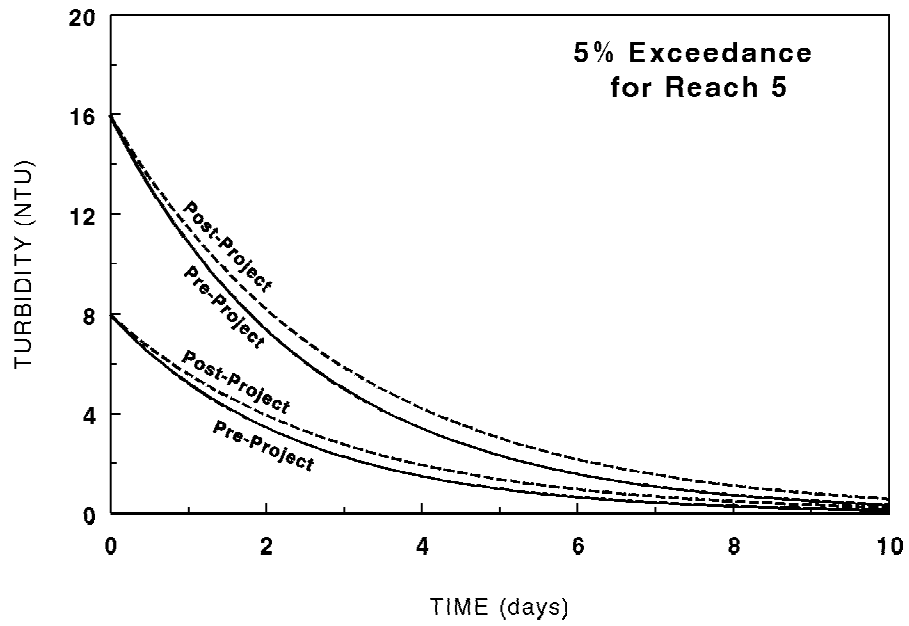


Figure 4. Turbidity response for 5% exceedance at Reach 5.

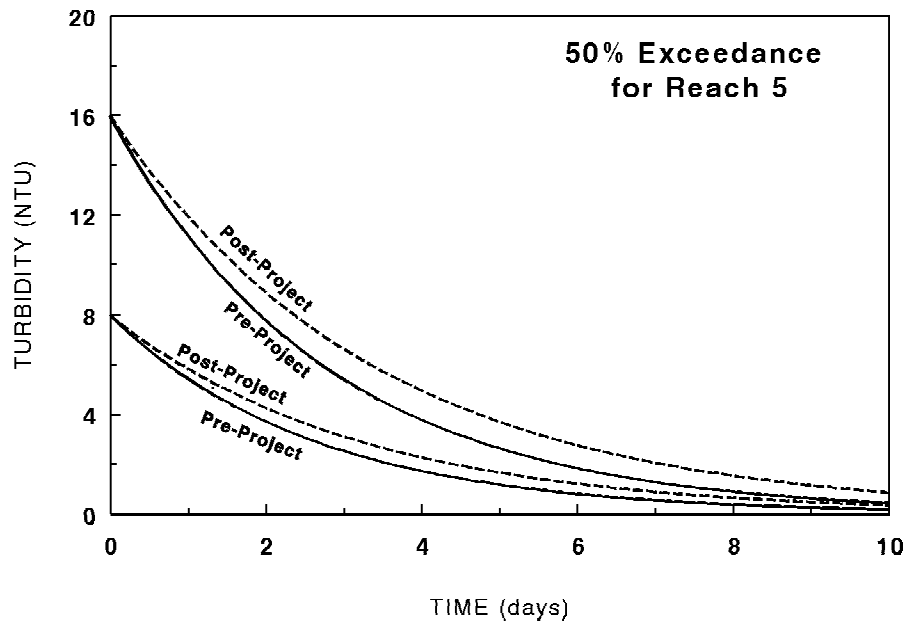


Figure 5. Turbidity response for 50% exceedance at Reach 5.

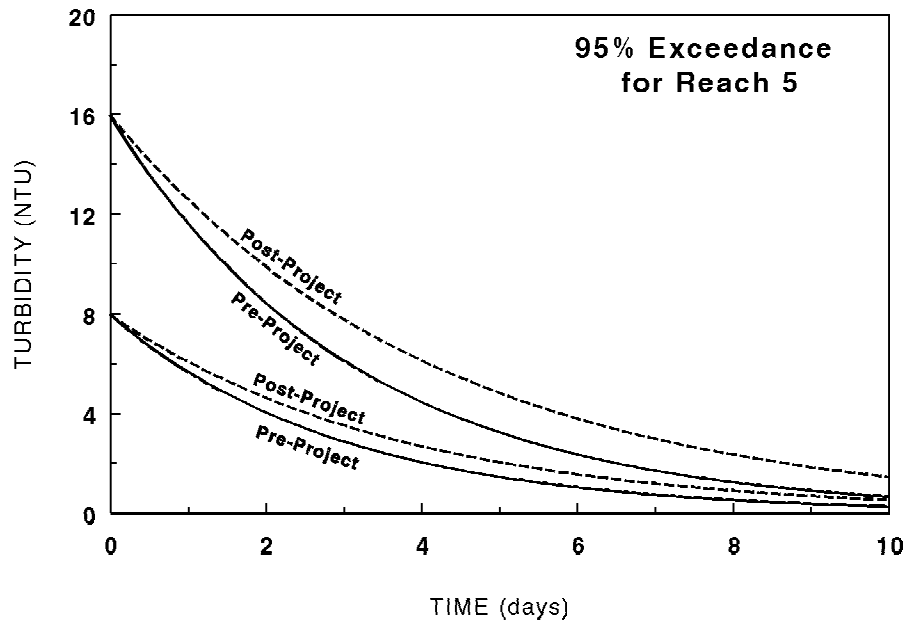


Figure 6. Turbidity response for 95% exceedance at Reach 5.

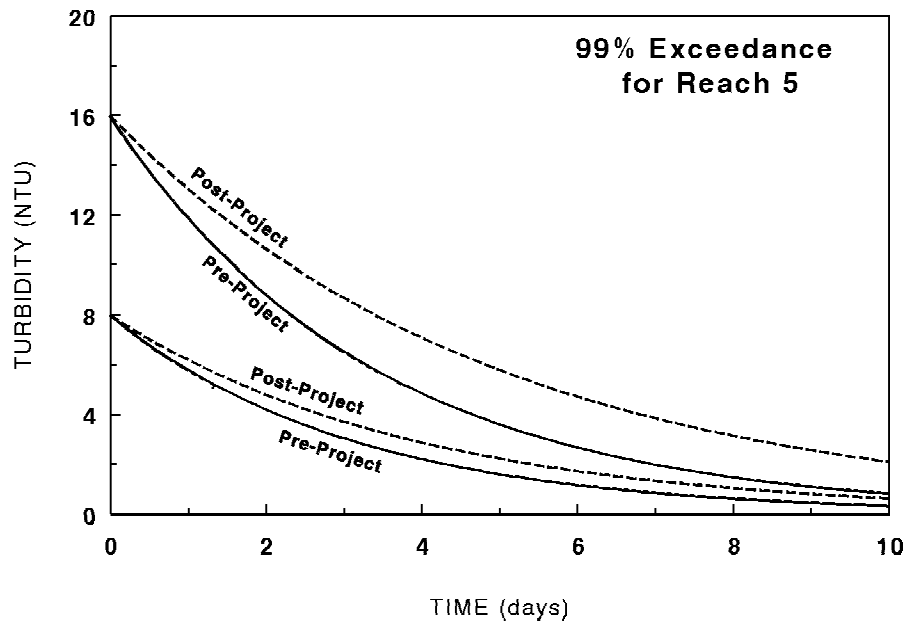


Figure 7. Turbidity response for 99% exceedance at Reach 5.

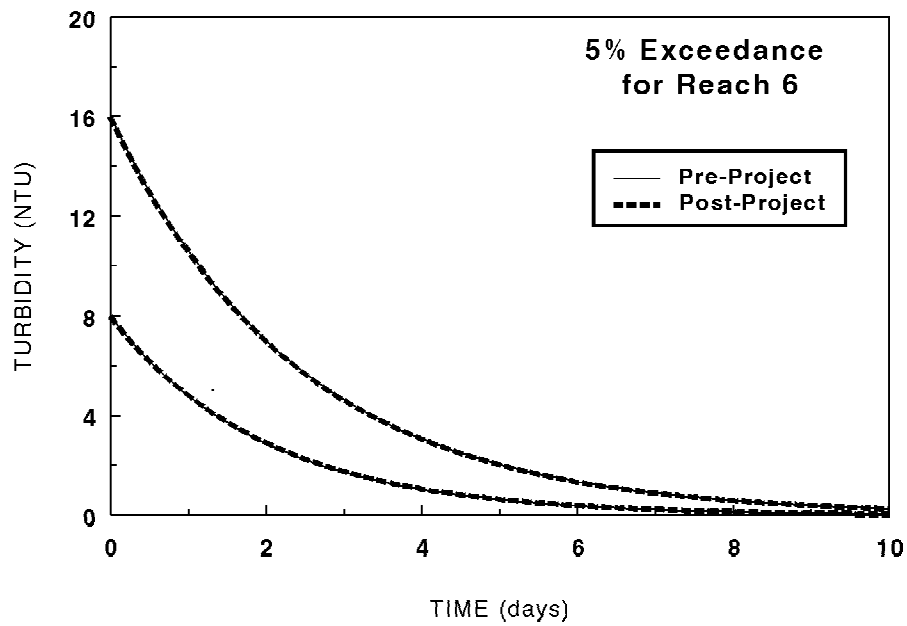


Figure 8. Turbidity response for 5% exceedance at Reach 6.

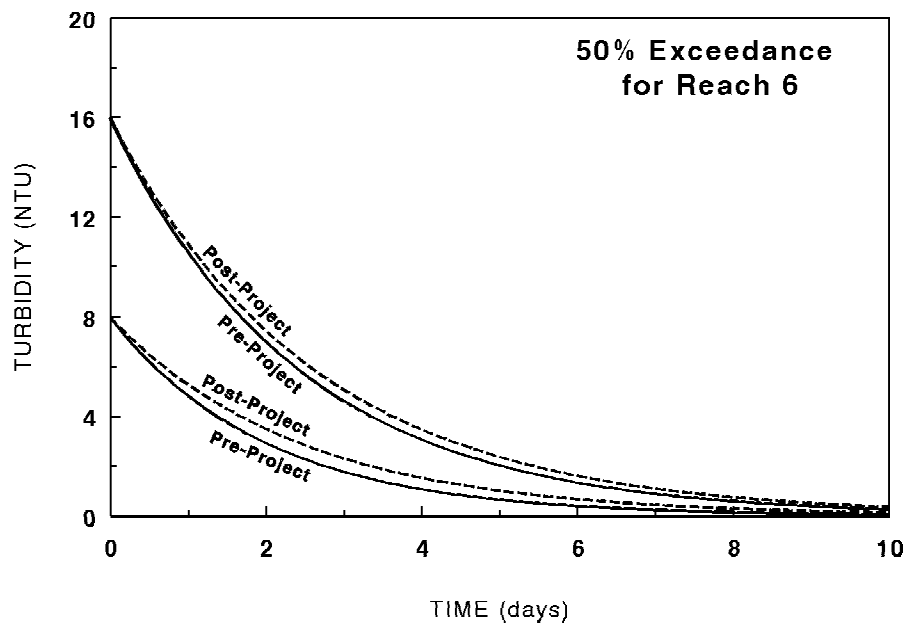


Figure 9. Turbidity response for 50% exceedance at Reach 6.

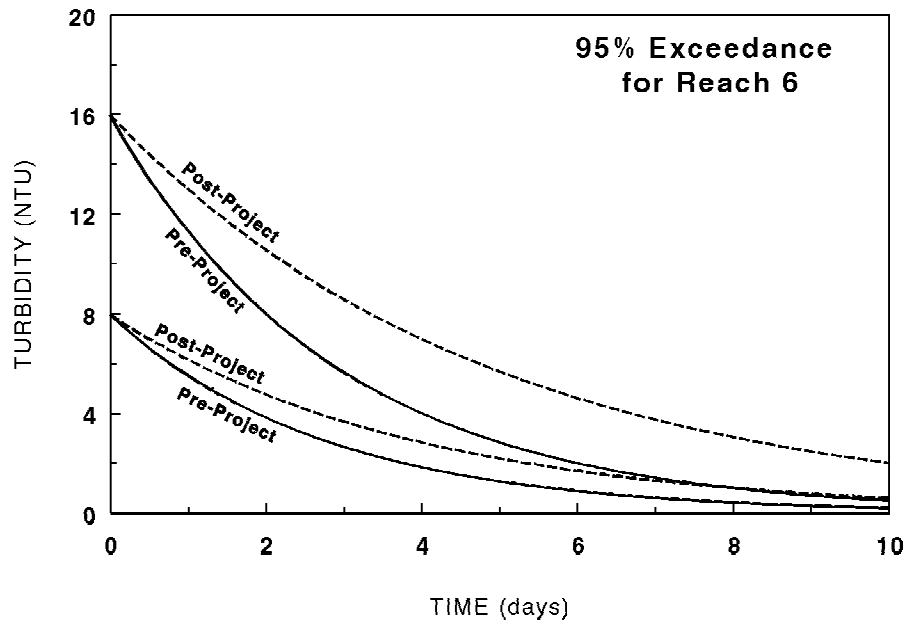


Figure 10. Turbidity response for 95% exceedance at Reach 6.

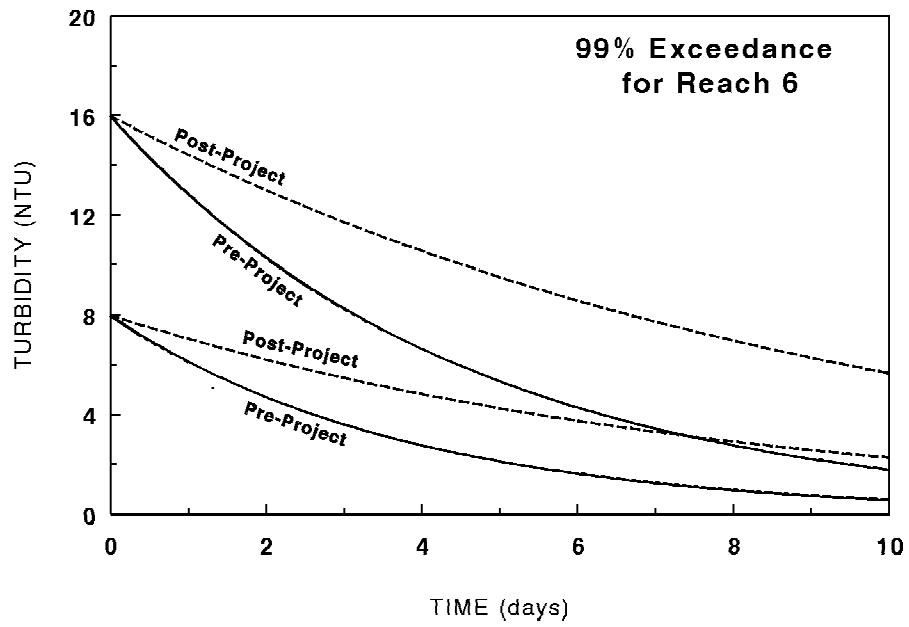


Figure 11. Turbidity response for 99% exceedance at Reach 6.

Table 10. Comparisons of Pre- and Post-Project Turbidity

Location	Frequency Concentration Exceeded (percent)	8 NTU Initial Turbidity		16 NTU Initial Turbidity	
		Time of Maximum Difference (days)	Maximum Difference in Turbidity (NTU)	Time of Maximum Difference (days)	Maximum Difference in Turbidity (NTU)
Reach 5 Lake Texoma Dam	5	2.60	0.50	2.79	0.87
	50	2.88	0.58	3.08	1.22
	95	3.29	0.65	3.62	1.68
	99	3.48	0.67	4.04	2.24
Reach 6 Red River at Entrance to Lake Texoma	5	1.97	0.04	2.42	0.00
	50	2.20	0.57	2.52	0.47
	95	3.25	1.02	3.71	2.98
	99	5.34	2.14	6.48	4.31

maximum increase lasts several days. Disturbances about 5 percent of the time will yield a maximum increase over pre-project levels equal to about 10 percent of the initial turbidity resulting from the disturbance, occurring 3 to 4 days after the disturbance and lasting about a week at levels about 5 percent of the initial turbidity higher. About 1 percent of the time the maximum increase will be about 15 to 20 percent of the initial turbidity. Under these conditions increases of about 10 percent of the initial turbidity will last about 7 to 10 days. Under peak differences the post-project turbidity level may be about 50 percent (about 2 to 3 NTU) larger than the pre-project level.

These comparisons are based on laboratory sedimentation rates. Actual rates in the field would be expected to vary somewhat since there is more mixing and dispersion in Lake Texoma that may speed up sedimentation by mixing in more saline water or by providing flocculation, or slow the sedimentation by resuspending the particles and by requiring larger flocs for sedimentation. In addition, the surface turbidity may be influenced by the hydrodynamics of the lake which may cause the inflow to plunge, mix or ride on the surface.

6 CONCLUSIONS

The results of this study demonstrated that:

- a. A reduction in chlorides, and therefore a reduction in TDS, will contribute to a decrease in the sedimentation rate in the Lake Texoma. Over the range of reductions examined the sedimentation or turbidity decay rate varied by about a factor of three. This means that the slowest settling test condition in the laboratory would take about three times as long to achieve the same level of turbidity following a disturbance or introduction of turbidity.
- b. The sedimentation rate at the higher initial turbidity (16 NTU) was not significantly different from the sedimentation rate at the lower initial turbidity (8 NTU) for a given TDS concentration except at the lowest TDS concentration examined (519 mg/l). The sedimentation rate was smaller at a higher initial turbidity. This suggests that some mechanism of ion exchange or precipitation contributes to the coagulation and sedimentation.
- c. Since the sedimentation rates were significantly different as a function of TDS concentration, the final percent removal of turbidity after 7 days of settling were also significantly different as a function of TDS concentration. Similarly, as with sedimentation rates, the removal percentages at different initial turbidity levels were not significantly different.
- d. After 2 days of settling, the differences in the removal percentages at the various TDS concentrations with the lower initial turbidity were small but with the higher initial turbidity the differences were more significant. The difference in removal percentages at 2 days of settling were a function of initial turbidity.
- e. The differences in the final turbidity after 7 days of settling among the four levels of reductions examined were a maximum of 10 percent of initial turbidity of 8 NTU and 15 percent of initial turbidity of 16 NTU. The differences in the turbidity after 2 days of settling among the four levels of reductions examined were a maximum of 15 percent of initial turbidity of 8 NTU and 23 percent of initial turbidity of 16 NTU. Therefore, one might expect a small increase in turbidity, perhaps 1 to 3 NTU, at the lowest TDS concentrations.

- f. Comparison of responses to introduction of turbidity under pre- and post-project conditions showed little difference for 50 percent of the time. Post-project turbidity levels would be less than 1 NTU, generally less than 0.5 NTU, higher than pre-project levels. These elevated levels would last several days and start about two days after the introduction of turbidity based on the laboratory sedimentation rates.
- g. Comparison of responses to introduction of turbidity under less frequent conditions (1 to 5 percent of the time) shows greater differences in turbidity levels between pre- and post-project conditions. Differences in turbidity may be 10 to 20 percent of the initial turbidity higher at maximum difference. Differences as large as 5 percent of initial turbidity may last as long 5 to 10 days based on laboratory sedimentation rates. Under peak differences the post-project turbidity level may be about 50 percent (about 2 to 3 NTU) larger than the pre-project level.

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APPENDIX F: WATER QUALITY DATA
FROM THE ANALYTICAL LABORATORY

APPENDIX G: ELECTROPHORETIC MOBILITY DATA

